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# MEASUREMENT AND ANALYSIS OF CIRCUMSOLAR RADIATION

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# Measurement and Analysis of Circumsolar Radiation*

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## Introduction

Four instrument systems called "Circumsolar Telescopes" are used to measure the solar and circumsolar radiation for application to solar energy systems that employ lenses or mirrors to concentrate the incident sunlight. Circumsolar radiation results from the scattering of direct sunlight through small angles by atmospheric aerosols (dust, water droplets or ice crystals in thin clouds, etc.). The solar energy system will typically collect all of the direct solar radiation (that originating from the disk of the sun) plus some fraction of the circumsolar radiation. The exact fraction depends upon many factors, but primarily upon the angular size (field-of-view) of the receiver. A knowledge of the circumsolar radiation can be used as a factor in the optimization of a receiver design, as one measure of the suitability of a geographic region for concentrating systems, or as input to comparison studies of competing designs at a particular location.

The instrument systems were designed and constructed at Lawrence Berkeley Laboratory (LBL). Each system has a "scanning telescope" mounted on a precision solar tracker. The telescope is mechanically scanned thru an arc of $6^{o}$ with the sun at the center of the arc. A digitization of the brightness of the sun or circumsolar radiation is taken every 1.5′ of arc, with a complete scan taking one minute of time. Auxiliary instruments include a pyrheliometer and two pyranometers, one mounted in the usual horizontal postion and one tracking the sun. The telescope and pyrheliometer have matched ten position filter wheels: one open position, eight interference filters that divide the solar spectrum into eight intervals of roughly equal energy content, and one opaque filter to monitor detector noise. The data are recorded on magnetic tape, with one tape holding one week′s worth of data per telescope. The tapes are shipped to LBL for computer processing.

The telescopes have been primarily operated at locations for which the instruments can play a dual role: (1) characterization of a region or climate, and (2) providing of site specific data for proposed or actual concentrating solar energy systems.

The data are used at LBL and other DOE supported institutions (e.g., SERI) in considerations of the performance of concentrating systems. In order to extend the analyses to areas not covered by the instruments, efforts are underway to understand the relationship of the circumsolar radiation to atmospheric conditions and to other, more routine, solar and meteorological measurements.

## Measurement Program

Telescopes are in operation at Sandia Laboratories, Albuquerque [location of the Central Receiver Test Facility (CRTF) and other concentrating systems]; on

* Summary for the period April-September, 1979.

a Southern California Edison (SCE) building at Barstow, California [near the site of the future 10 $Mw_e$ Pilot Plant], and at Georgia Tech [site of a central receiver test facility]. LBL has continued to provide engineering and technical support for the instruments, and to routinely monitor the quality of the data.

The remaining telescope (designated Scope 3) is currently operating at LBL. This instrument has been refurbished, and a number of modifications have been made to improve weatherability. An automated sunphotometer (of the Volz type) was installed and appears to be operating normally. Some electronic modifications were made to increase the precision with which the output of the pyrheliometer is recorded. Plans call for the telescope to be moved to SERI, but SERI has been experiencing some difficulties in preparing a suitable site for solar radiation measurements.

A request was received from the Jet Propulsion Laboratory (JPL) to have a telescope located at their test facility for small scale concentrating systems (e.g., parabaloidal dishes). The test facility, located at Edwards Air Force Base, is about 50 miles east of Barstow. An agreement was reached among JPL, DOE, SCE, Sandia, Livermore (technical manager for the pilot plant) and LBL to move the telescope at Barstow (Scope 4) to Edwards until such time as heliostats are installed at the pilot plant. The move is currently scheduled for the middle of October. [While this report was in preparation, it was decided to move Scope 3 from LBL to Edwards and to return Scope 4 to LBL. The plan would then be to refurbish this latter instrument, which has been operating in the Mohave desert for over three years.]

Sandia, Albuquerque developed an electronics interface from the telescope to the data acquisition system for the CRTF. Thus the telescope at Albuquerque is now "on-line" during receiver or heliostat tests.

The telescopes required somewhat more than the usual amount of repairs during this report period. In particular, the magnetic tape recorders began to malfunction. A program was initiated to return the machines to the manufacturer for rehabilitation in a round-robin fashion. A spare recorder has been utilized to minimize the loss of data during this process.

<u>Data Processing</u>

Some changes have been made in the data processing chain. Heretofore, the original tapes from the telescopes were stored for some time in the LBL computer center's tape library and were the basis for further processing. Now, the information from these tapes is copied "as-is" onto high density (6250 BPI) tapes at the same time as the initial processing for quality control. These latter tapes, designated RAW tapes, can each hold about six month's worth of data from one telescope. In addition to considerably reducing tape storage requirements, the RAW tapes are much easier to access.

The RAW tapes are used to fill requests for recently taken data (e.g., a request from Sandia for data taken during a test at the CRTF when the on-line data acquisition system was not operating properly). These tapes are also the starting point for subsequent data processing. Briefly, various organizational difficulties are fixed (e.g., erroneous dates are corrected), and the data transferred to so-called FIX tapes (formerly called GSS tapes). The FIX tapes are then used in the creation of the preliminary Reduced Data Base (RDB), in which calibration factors are applied and the data are condensed. Various statistical methods are then used to look for and, when necessary, devise correction factors for faulty data. A revised RDB is then produced and is the input to statistical analyses of the effect of circumsolar radiation on concentrating solar energy systems.

As of Oct. 1, the FIX tapes were complete up through June, 1979, the preliminary version of the RDB thru December, 1978; and the revised version of the RDB thru June, 1978.

## Data Supplied to Others

SERI was able to read and analyze a sample tape of hourly average values that had been prepared last spring. A tape with additional data was sent to SERI in June.

The tape generated last winter for Watt Engineering proved insufficient for their expanded analysis efforts. Watt and an associate came to LBL in June and, working with LBL personnel, were able to prepare a more complete data base on floppy disks suitable for their micro-computer.

The tape of hourly averages (pyrheliometer and the corresponding horizontal pyranometer readings) that had been prepared for Sandia, Albuquerque had a subtle flaw in the algorithm used to bin the data into hourly intervals. A revised tape was written and sent to Sandia.

Individual scans of the telescope, taken during tests at the CRTF of the Boeing gas receiver, were processed and sent to Boeing. Scans taken during recent comparisons between contending heliostat designs for the Barstow 10 $Mw_e$ pilot plant were sent to Sandia to cover a period of time when their on-line system was not functioning properly.

## Data Analysis

Summaries of previous review meetings have presented analyses of the average effect of circumsolar radiation on solar energy systems employing concentrating collectors. In addition, the approach to and the results of such analyses were presented at the Atlanta ISES meeting (Grether, 1979). A different approach, based on data supplied to SERI by LBL (see above), was also presented at the Atlanta meeting (Rabl, 1979). Summarized here is part of the effort to characterize individual measurements of the circumsolar radiation, so that these measurements can be related to atmospheric phenomena.

It has been known for some time that if the scans (brightness of the solar and circumsolar radiation vs angular distance from the center of the sun) are displayed in log-log space, then the circumsolar radiation can often be approximated by a straight line. Figure 1 (a) shows a sample scan for a clear sky (low circumsolar level) and 1 (b) for a hazy sky (high circumsolar level).

The solid, vertical line represents an "effective radius" of the sun. [The center of the sun is off-scale.] The straight lines thru the data points in the circumsolar region and the corresponding slope are from a simple computer algorithm. In general, such a straight line provides a reasonable description of the circumsolar radiation for angles greater than $1^{o}$, in log-log space. The slope of the line then provides one method of characterizing the data, in addition to the circumsolar ratio [ratio of energy content in the circumsolar region to energy content of the solar + circumsolar, C/(C+S) in the figure], and the normal incidence reading of a pyrheliometer [NI in the figure]. In terms of scattering properties of aerosols (i.e., Mie theory) a relatively steeper slope indicates that relatively larger particles are responsible for the scattering.

Watt (1979) has raised the possibility that there might be a relatively simple relationship between this "circumsolar slope" and airmass. Figure 2 (a) shows a plot of circumsolar slope vs airmass for a month's worth of data from Barstow. Of particular note is that, especially for relatively small air masses, there are two reasonably distinct groups of slopes. One of these groups is centered at about 1.5 and the other at 2.5. Figure 2(b) helps explain the origin of these two groups. Plotted in this figure is the slope versus the circumsolar ratio. The large slopes are seen to be associated with high circumsolar ratios. The interpretation is that for the atmospheric conditions that give rise to high levels of circumsolar radiation (e.g., haze, thin clouds) the light-scattering aerosols tend to be rather large. In any case, no simple description of the dependence of slope on airmass is possible.

Colored Filter Data

As discussed at the last meeting, efforts are underway to calibrate the data taken thru the the colored filters. As one part of this effort, the filters on the instrument returned to LBL (Scope 3) have been examined for evidence of degradation. Filter transmission curves in the form of stripcharts were obtained on a Cary 17 Spectrophotometer, and then digitized. These curves can then be compared to the ones supplied by the manufacturer when the filters were new. Figure 3 shows the situation for two of the eight filters from the pyrheliometer filter wheel. The solid curves are the manufacturer's measurements, and the dotted curves the measurements made after the telescope had been returned to LBL. Filter #2 shows some change in overall transmission and in the cut-on and cut-off wavelengths. On the other hand, for filter #8, there was essentially no change. Of the other six filters, one shows a degradation somewhat worse that for filter #2. The remaining five show a change roughly intermediate to that for filters #2 and 8.

The next step is to develop a method of using the data themselves to provide a calibration factor that tracks the effective change in filter characteristics with respect to time. The intent is to develop a modified "Langley Plot" method using clear day data. The difficulty is that for the relatively broad pass bands of these filters, the extrapolation to zero air mass is not as linear (on a semi-log plot) as for monochromatic light. Work has proceeded on using version 3B of the atmospheric transmission program Lowtran (Selby, 1975) as a guide to the proper form of the extrapolation.

Lowtran can be readily combined with an extraterrestrial solar spectrum and then used to estimate the solar radiation per unit wavelength at ground level for a specified set of atmospheric conditions. [See, for example, Ireland (1979).] Preliminary efforts have involved comparing the calculations of such a modified version of Lowtran to actual pyrheliometer data for specific clear days. Figure 4 shows the comparison for July 24, 1978 at Barstow (Scope 4) for the clear (or open) filter and for three colored filters. [The solid curves are from the pyrheliometer, and the dotted ones from the Lowtran calculation.] In this comparison the atmospheric model is "Midlatitude summer," with parameters scaled to match the observed temperature, dew point and barometric pressure. The extraterrestrial solar spectrum is that of Theakakara (1975), scaled to a solar constant of 1367 $W/m^2$ and then corrected for the actual earth-sun distance. To simplify this preliminary comparison, the attenuation from atmospheric aerosols has been neglected.

Consider the graph in Fig. 4 for the clear (open) filter. The calculation based on Lowtran is obviously higher than the data. Now consider the graphs for the colored filters. For this comparison, the predicted solar spectrum from Lowtran has been folded-in with the manufacturer-supplied transmission curve so as to simulate the reading of a pyrheliometer taken thru the corresponding filter. As is indicated by Figure 4, the Lowtran calculation tends to agree with the data at the blue end of the solar spectrum, and to yield higher values than the pyrheliometer towards the red/ir end of the spectrum. There are several possible explanations for the disagreement:

(1) The aerosol attenuation was neglected. The atmospheric aerosol load could be "adjusted" to yield better agreement for the clear filter and red/ir filter measurements, but the agreement would then be poorer at the blue end of the spectrum for almost any reasonable aerosol scattering model.

(2) The scaling of Lowtran's internal prescriptions (e.g., vertical water vapor profile) from ground-based measurements may not be appropriate.

(3) The filters may have significantly changed their characteristics, and in a manner different than those from Scope 3. However, the comparison for the clear filter is independent of individual filter characteristics.

(4) There is some difficulty with Lowtran.

It is hoped that a modest amount of additional effort will yield closer agreement, or at least a reduction in the number of possible problems. In particular, the filters from Scope 4 can be measured when that instrument is returned to LBL.

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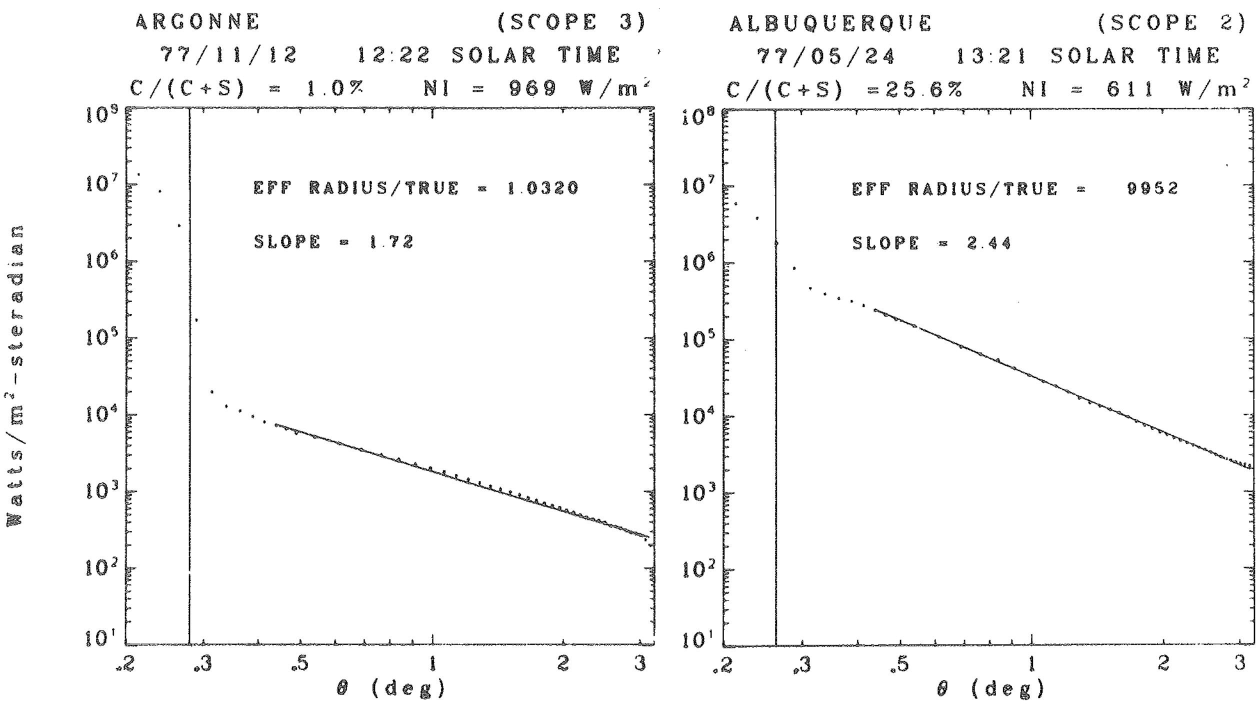



Figure 1

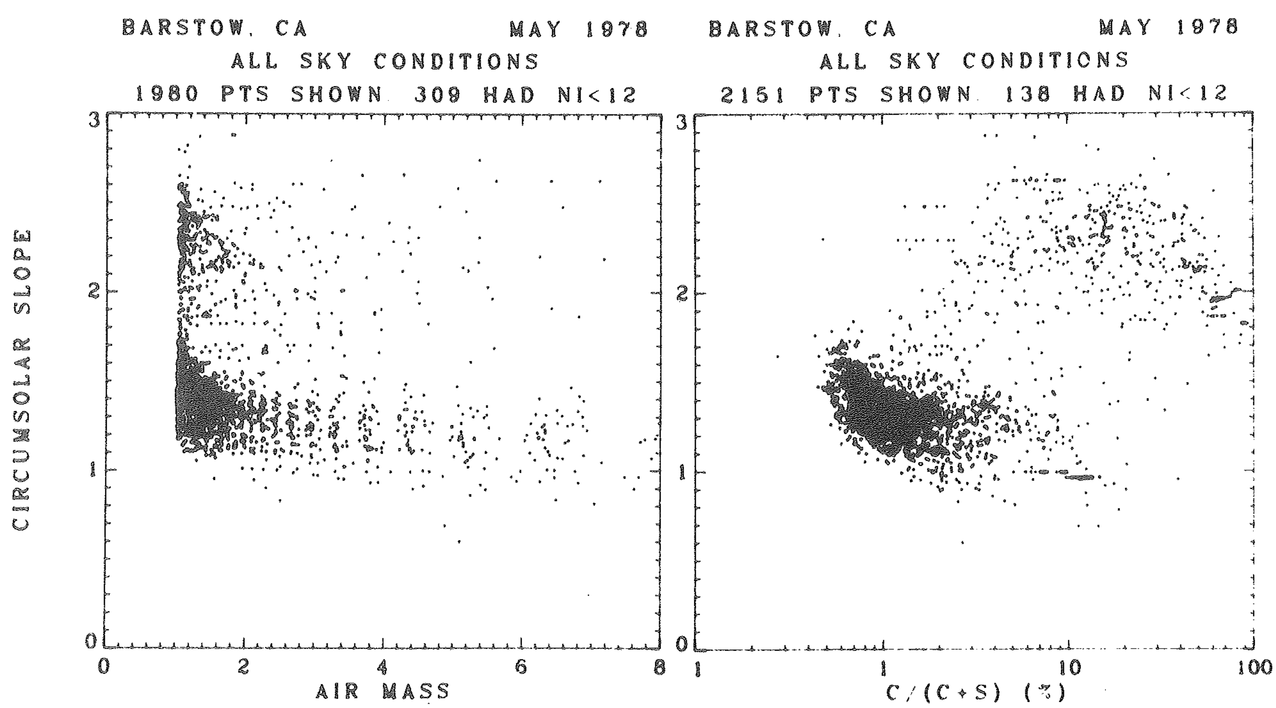
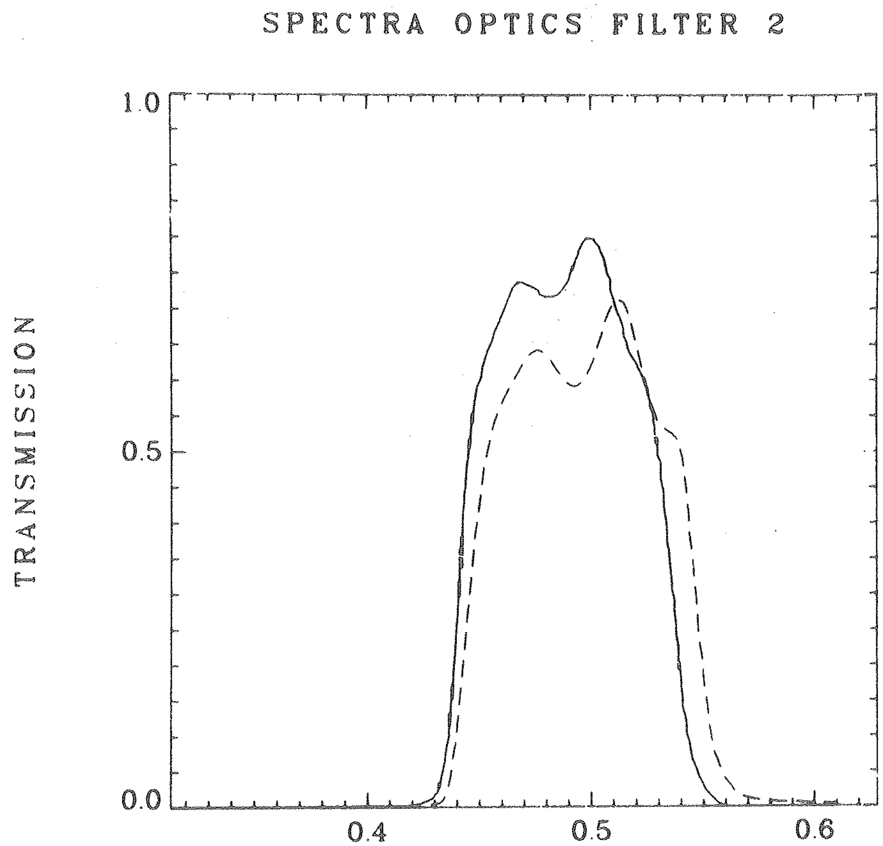



Figure 2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1.0
0.5
0.0
TRANSMISSION
0.4
0.5
0.6

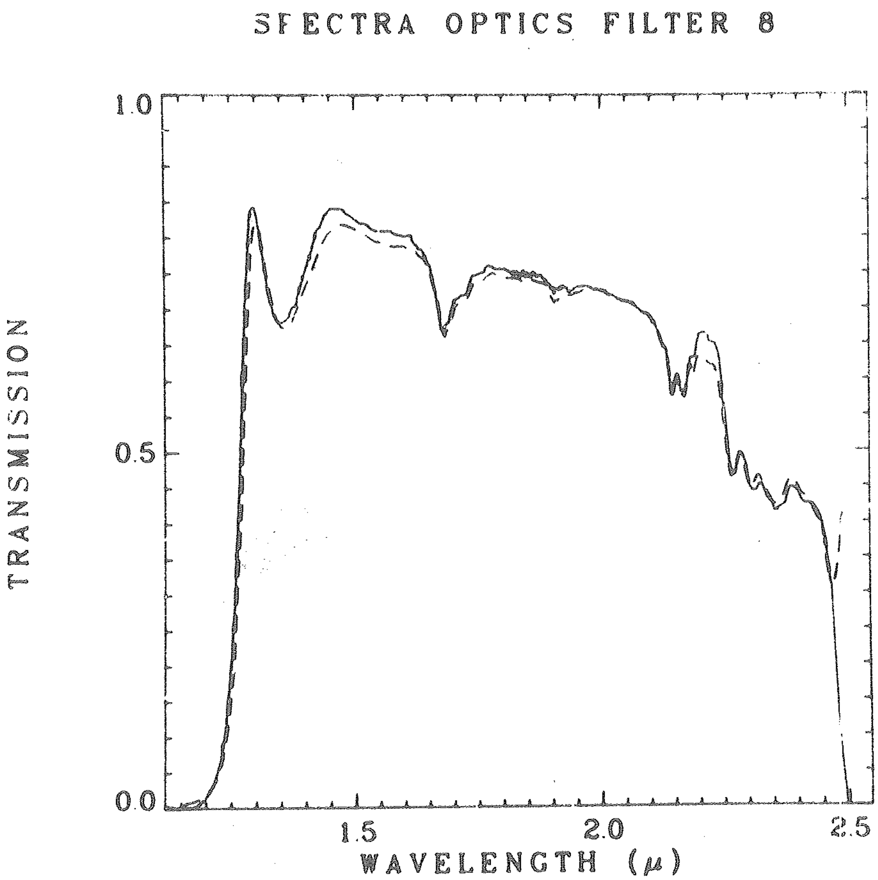
SPECTRA OPTICS FILTER 8
1.0
0.5
0.0
TRANSMISSION
1.5
2.0
2.5
WAVELENGTH (μ)

Figure 3

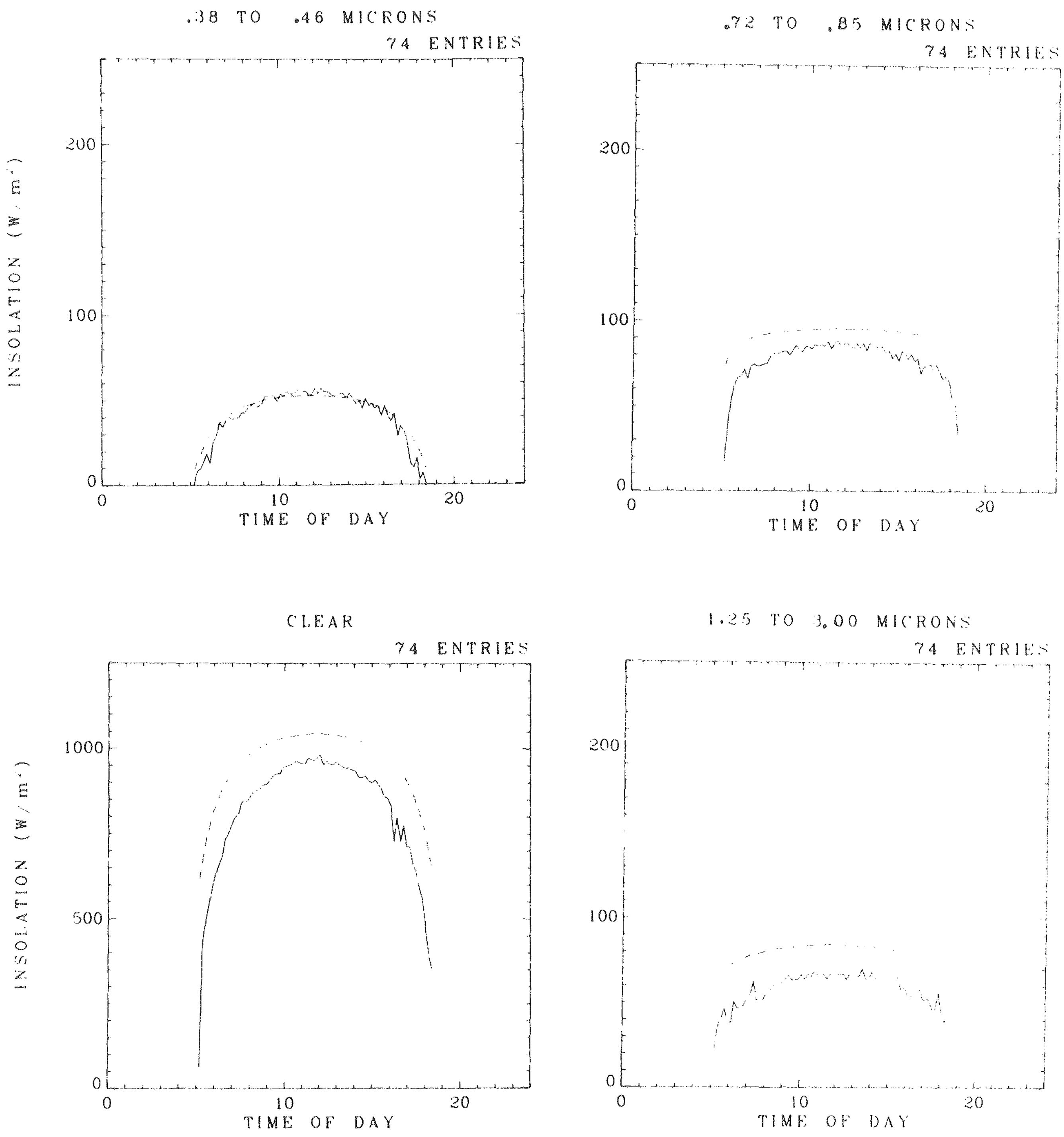
.38 TO .46 MICRONS
74 ENTRIES
.72 TO .85 MICRONS
74 ENTRIES
CLEAR
74 ENTRIES
1.25 TO 3.00 MICRONS
74 ENTRIES
INSOLATION (W/m²)
TIME OF DAY
0
10
20
100
200
500
1000

Figure 4